MERGING CLUSTERS OF THE DARC SAMPLE: studying the formation of galaxy systems and their brightest galaxies

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Abstract

Extended, diffuse radio emissions (halos and relics) embedded in galaxy clusters are rare phenomena. Here I present a few results of the DARC program, aimed to study the internal Dynamics Analysis of "Radio"-Clusters mainly based on a TNG program (spectroscopic data for 20 clusters at z=0.1-0.3). The study of kinematics of member galaxies show that DARC clusters are examples of very substructured systems and allow us to detect and weight the intervening subclusters as well as to determine their relative motions and projected geometry. The brightest galaxies in DARC clusters are (amost) always related to the subclusters we detect through our 3D analysis.

1 Introduction

Merging processes constitute an essential ingredient of the evolution of galaxy clusters (see Feretti et al. 2002 and refs. therein). An interesting aspect of these phenomena is the possible connection between cluster mergers and extended ($\sim$ 1 Mpc), diffuse radio sources: halos and relics. The synchrotron radio emission of these sources demonstrates the existence of large-scale cluster magnetic fields and of widespread relativistic particles. Cluster mergers have been proposed to provide the large amount of energy necessary for electron reacceleration to relativistic energies and for magnetic field amplification (Tribble 1993). Radio relics, which are polarized and elongated radio sources located in the cluster peripheral regions, seem to be directly associated with merger shocks (e.g., Ensslin et al. 1998). Radio halos, unpolarized sources that permeate the cluster volume in a similar way to the X-ray emitting gas (intracluster medium, hereafter ICM), are more likely to be associated with the turbulence following a cluster merger (e.g., Cassano & Brunetti 2005). However, the precise radio halos/relics formation scenario remains unclear because diffuse radio sources are quite uncommon and one has been able to study these phenomena only recently on the basis of a sufficient statistics (few dozen clusters up to $z \sim 0.4$, e.g., Giovannini et al. 2009). It is expected that new radio telescopes will largely increase the statistics of diffuse sources (e.g., LOFAR).

From the observational point of view, there is growing evidence of the connection between diffuse radio emission and cluster merging, above all from X-ray observations (Feretti 2008 and refs. therein).

Optical (photometric and spectroscopic) data on cluster galaxies are a powerful way to investigate the presence and the dynamics of cluster mergers, too (e.g., Girardi & Biviano 2002). The optical information is really complementary to X-ray information since galaxies and the ICM (i.e. $\sim$ collisionless and collisional cluster components) react on different time-scales during a merger.

2 The DARC project

In the above context, we are conducting an intensive observational and data analysis program to study the internal dynamics of clusters with diffuse radio emission by using member galaxies (see also the web site of the DARC project: $http://adlibitum.oat.ts.astro.it/girardi/darc$).

The DARC project is mainly based on spectroscopic data acquired at the 4m class Italian telescope, TNG, which, equipped with DOLORES/MOS instrumentation, is well suited to study the internal dynamics of clusters exhibiting radio halos/relics having redshift in the range of z=0.1-0.3, i.e. a large part of known clusters exhibiting these phenomena.

For each DARC cluster we sampled a significant fraction of the cluster virial region with about 100 galaxies having redshifts, magnitudes, and colors. Additional information comes from the equivalent width (EW) of the relevant lines for basic spectral characteristics and from the analysis of the cluster outskirts, as obtained from large-field multiband-photometry at the wide field camera of the INT telescope or available in the Sloan Digital Sky Survey.

For each cluster, we obtain: a) the estimate of global optical and dynamical properties (e.g., Girardi et al. 1998); b) the detection and significance of optical substructures; c) the membership and dynamical properties of individual substructures. In the specific case of major cluster collisions we can estimate: d) the projected direction of the merger axis; e) the projected separation of subclusters; f) the individual mass of the subclusters and thus the mass ratio of the merger; g) the line-of-sight (LOS) velocity difference between the subclusters.

For each cluster, information about the ICM hot component is available in public literature or obtained from data in public archives (e.g., the Chandra archive). The comparison between X-ray and optical data (and results from numerical simulations) is very useful to estimate the age of the merger. We discuss our findings in the framework of a multiwavelength approach, i.e. cf. with X-ray, radio, and gravitational lensing results.

3 Results

In the context of the DARC project we have already analyzed 16 clusters (Abell 115, 209, 520, 545, 610, 697, 725, 796, 773, 959, 1240, 2219, 2254, 2294, 2345, 2744) and the study of other four clusters is going on).

To date our results can be summarized as:

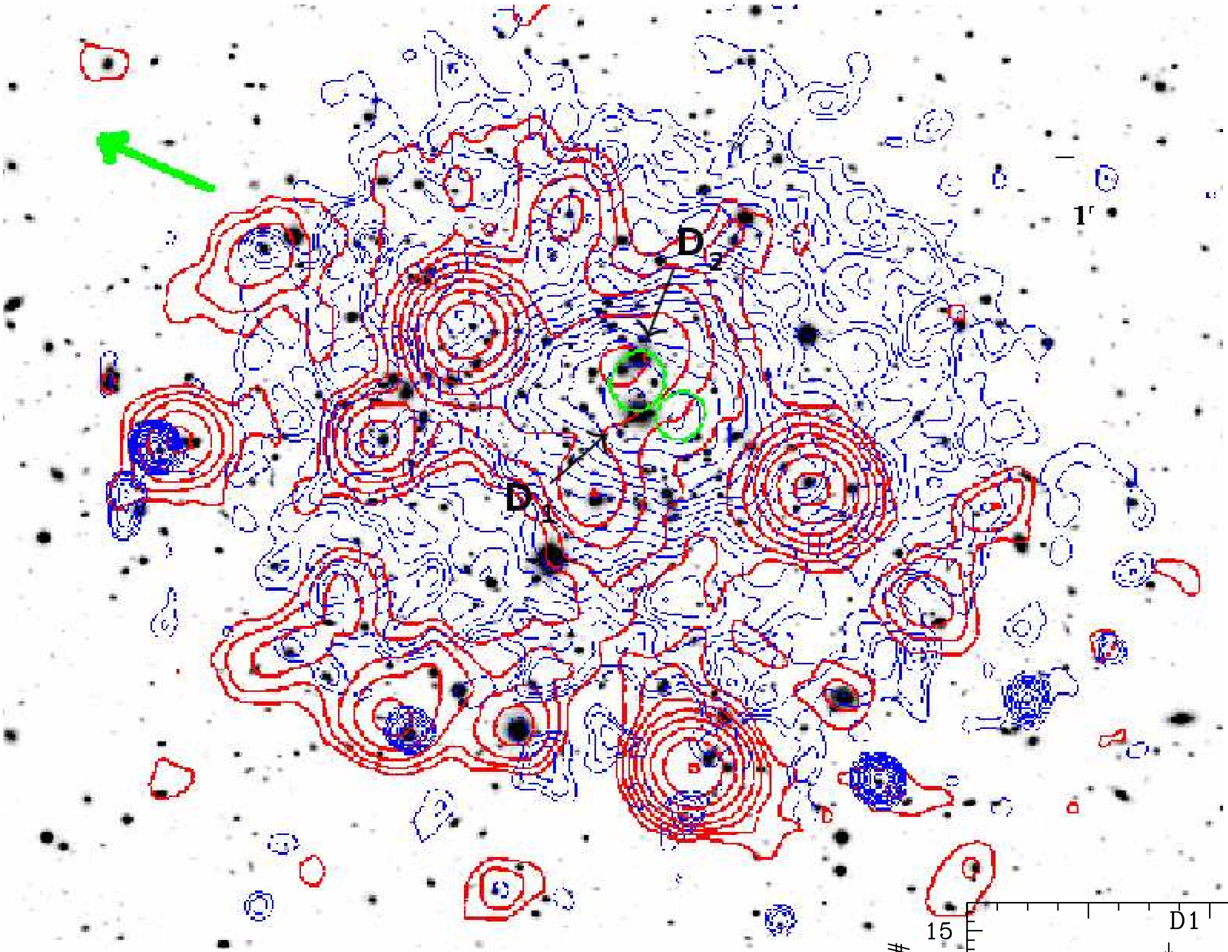
- Most DARC clusters have a high gravitational mass, i.e. $\sim$ 1-4 $\times 10^{15}$ h_{70}^{-1} $M_{\odot}$ within R_{200}).
- All DARC clusters show presence of strong substructure and for most of them we can detect the intervening subclusters. In the well studied cases, the observational scenario agrees with the DARC clusters being in a post-merger phase, few Gyr after the core-core passage, and with the rest-frame velocity difference between the subclusters of the order of 1000-4000 km s^{-1}. Our conclusion supports the view of the connection between extended radio emission and energetic merging phenomena in galaxy clusters.
- **We find that the subclusters are (very often) traced by their brightest/dominant galaxies (BCGs) and that the evolution of galaxy systems is parallel to the evolution of their BCGs: i.e., i) two distant - in space and/or in velocity - BCGs correspond to two well distinct subclusters; ii) two close BCGs - or one elongated BCG - correspond to a substructured cluster where the intervening subclusters (or more likely their remnants) are detectable with difficulty. We interpret these two families of clusters with two different merger stages (less and more advanced, respectively).**

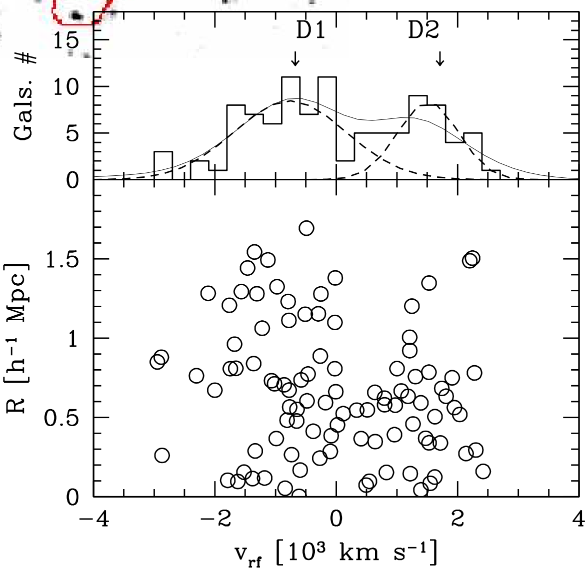
Hereafter we show a few examples of DARC clusters.

Abell 773: a LOS merging cluster with a radio halo.

The velocity distribution of cluster galaxies shows two peaks at v ∼65000 and ∼67500 km s^{-1}, **corresponding to the velocities of the two dominant galaxies D1 and D2.** Our analysis of Chandra data shows the presence of two very close peaks in the core and the elongation of the X-ray emission in the ENE-WSW direction. Our results suggest we are looking at a one, likely two groups in advance phase of merging with a main cluster with an impact velocity is $\Delta v_{\rm rf} \sim 2500$ km s^{-1}.

See Barrena et al. (2007, A&A, 467, 37) for other details.





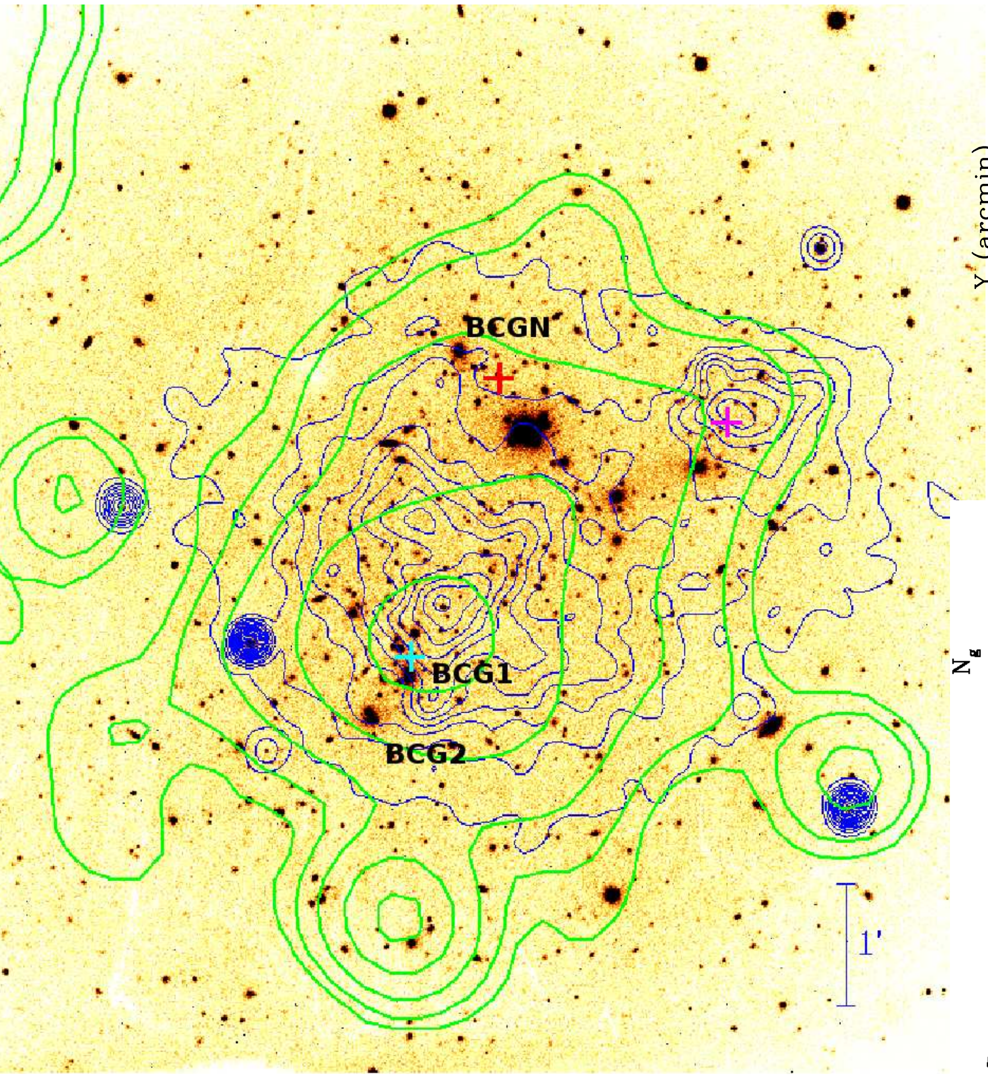
UPPER: INT *R*-band image of the cluster A773 with, superimposed, the contour levels of the Chandra image (blue) with the two separated peaks (green), and the contour levels of the Radio image (red). The direction of the close cluster A782 is also shown. North is at top and East to left.

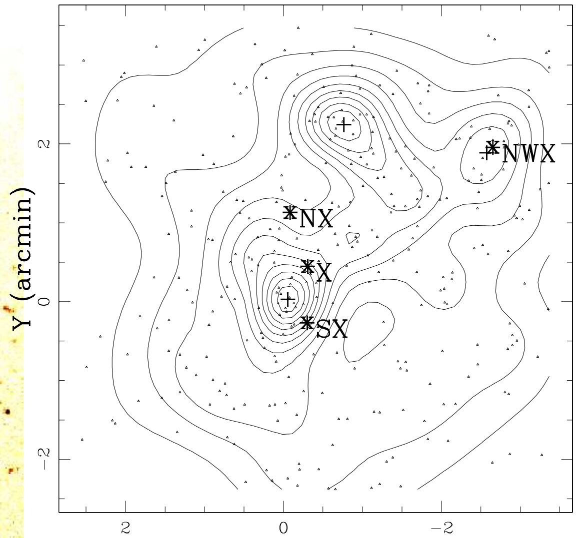
RIGHT: Velocity distribution of cluster galaxies, **where the two peaks are centered around the velocities of the two dominant galaxies.**

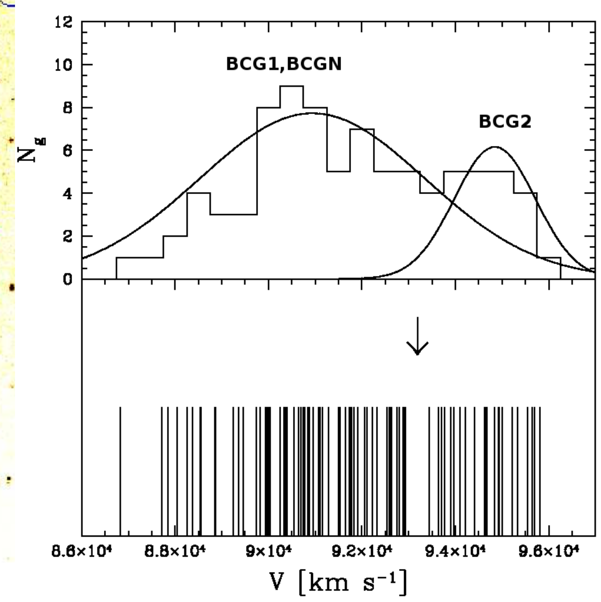
Abell 2744: a merging cluster with halo+relic.

We compute the line-of-sight (LOS) velocity dispersion of galaxies, $\sigma_V = 1767^{+121}_{-99}$ km s^{-1}. Our analysis shows the presence of two galaxy-clumps of different mean LOS velocities $\Delta V \sim 4000$ km s^{-1} . We detect a main, low-velocity clump with $\sigma_V \sim$ 1200-1300 km s^{-1} and a secondary, high-velocity clump with $\sigma_V =$ 500-800 km s^{-1}. **The two central BCG1 and BCG2 are associated with the two velocity peaks**. Our results suggest a merging scenario of two clumps with a mass ratio of 3:1 and a LOS impact velocity of $\Delta V_{rf} \sim 3000$ km s^{-1}, likely observed just after the core passage. **A northern clump, with a bright galaxy BCGN**, is detected but only in the 2D analysis due to the poor number of redshifts in that region.

See Boschin et al. (2006, A&A, 449, 461) for other details.







LEFT: NTT R-band image of the cluster A2744 with, superimposed, the contour levels of the Chandra archival image (blue contours, see Kempner & David 2004) and of a VLA radio image (green contours by Govoni et al. 2001, the radio halo). The three gray crosses indicate the position of the three peaks detected in the 2D galaxy distribution.

UPPER RIGHT: Spatial distribution on the sky and relative isodensity contour map with position of X-ray peaks (crosses).

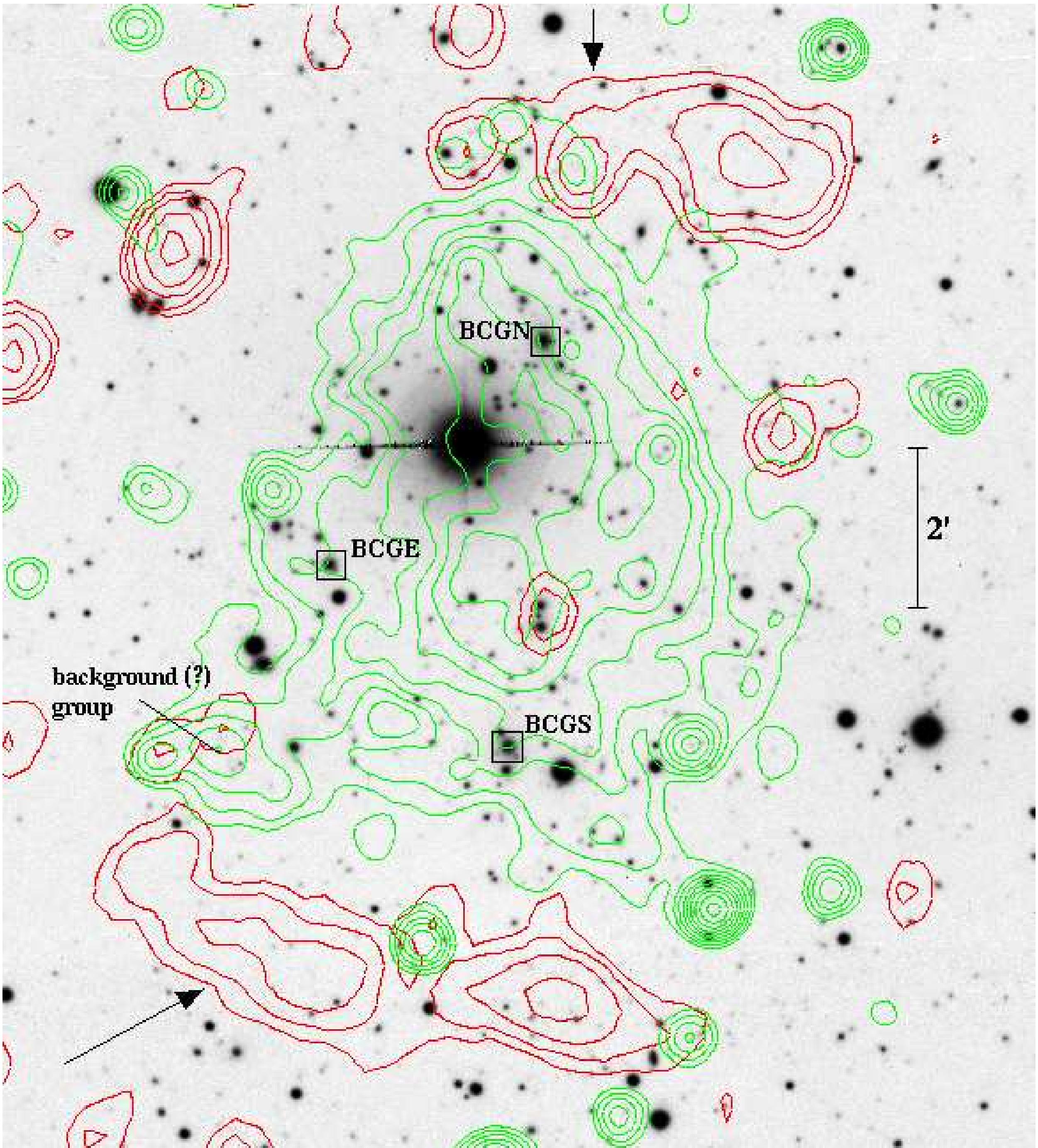
LOWER RIGHT: Velocity distribution of cluster galaxies.

The recent study by Owers et al. (2011) based on a larger number of redshifts shows that the main part of the low velocity subcluster is connected with the northern 2D group (hosing the BCG33), while the central group (hosting the BCG1) is likely a tidal debris due to the impact. **Thus, the low velocity subcluster is likely destroyed during the merger, each part having its BCG**.

Abell 1240: a cluster with symmetric double radio relics.

We estimate a LOS $\sigma_V \sim 870$ km s^{-1}. Abell 1240 is shown to have **a bimodal structure with two galaxy clumps, each dominated by a brightest cluster galaxy, BCGN and BCGS, roughly aligned along the N-S direction**, the same as defined by the elongation of its X-ray surface brightness (peaked between the two galaxy subclusters, Chandra archive data) and the axis of symmetry of the relics. **A minor clump is likely associated with the third bright galaxy (BCGE).** The two-body model agrees with the hypothesis that we are looking at a cluster merger that occurred largely in the plane of the sky, the two galaxy clumps being separated by a rest-frame velocity difference $V_{\rm rf} \sim 2000$ km s^{-1} at a time of 0.3 Gyr after the crossing core. The merging axis is perpendicular to the radio relics strongly supporting support the "outgoing merger shocks" model.

See Barrena et al. (2009, A&A, 503, 357) for other details.



INT R-band image of the cluster A1240 (North at the top and East to the left) with, superimposed, the contour levels of the Chandra image (green contours) and the contour levels of a VLA radio image at 1.4 GHz (red contours; Bonafede et al. 2009). Arrows show the positions of the two radio relics. Boxes highlight the brightest galaxies of A1240: BCGN, BCGS, and the third, minor BCGE.

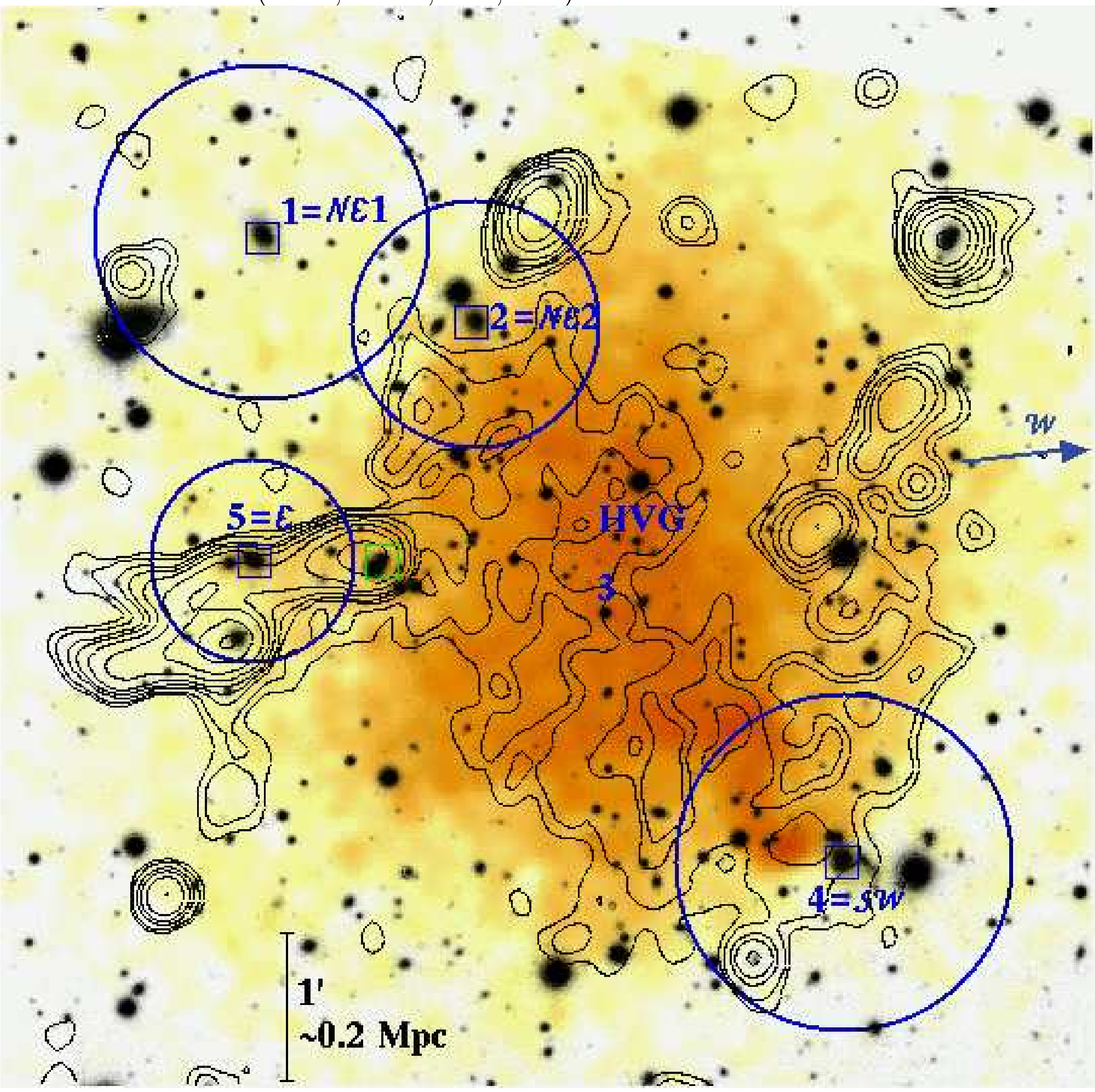
Abell 520: a cluster at the crossing of three LSS filaments.

Our analysis is based on redshift data for 293 galaxies in the cluster field. We detect the presence of a high velocity group (HVG) with a rest-frame relative LOS velocity of $v_{rf} \sim 2000$ km s^{-1} with respect to the main system (MS). We also find that the MS shows evidence of subclumps along two preferred directions. The main, complex structure $\mathcal{NE}1+\mathcal{NE}2$ and the $\mathcal{SW}$ structure (at $v_{rf} \sim +1100$ km s^{-1}) define the NE-SW direction, the same of the merger suggested by X-ray and radio data. The $\mathcal{E}$ and $\mathcal{W}$ structures define the E-W direction.

Moreover, we find no dynamical trace of the lensing dark core suggested by Mahdavi et al. (2007). Rather, the HVG and a minor MS group, having different velocities, are roughly centered in the same position of the lensing dark core, i.e. are somewhat aligned with the LOS.

Our results suggest that we are looking at a cluster forming at the crossing of three filaments of the large scale structure, **each intervening subclump having its BCG**.

See Girardi et al. (2008, A&A, 491, 379) for other details.



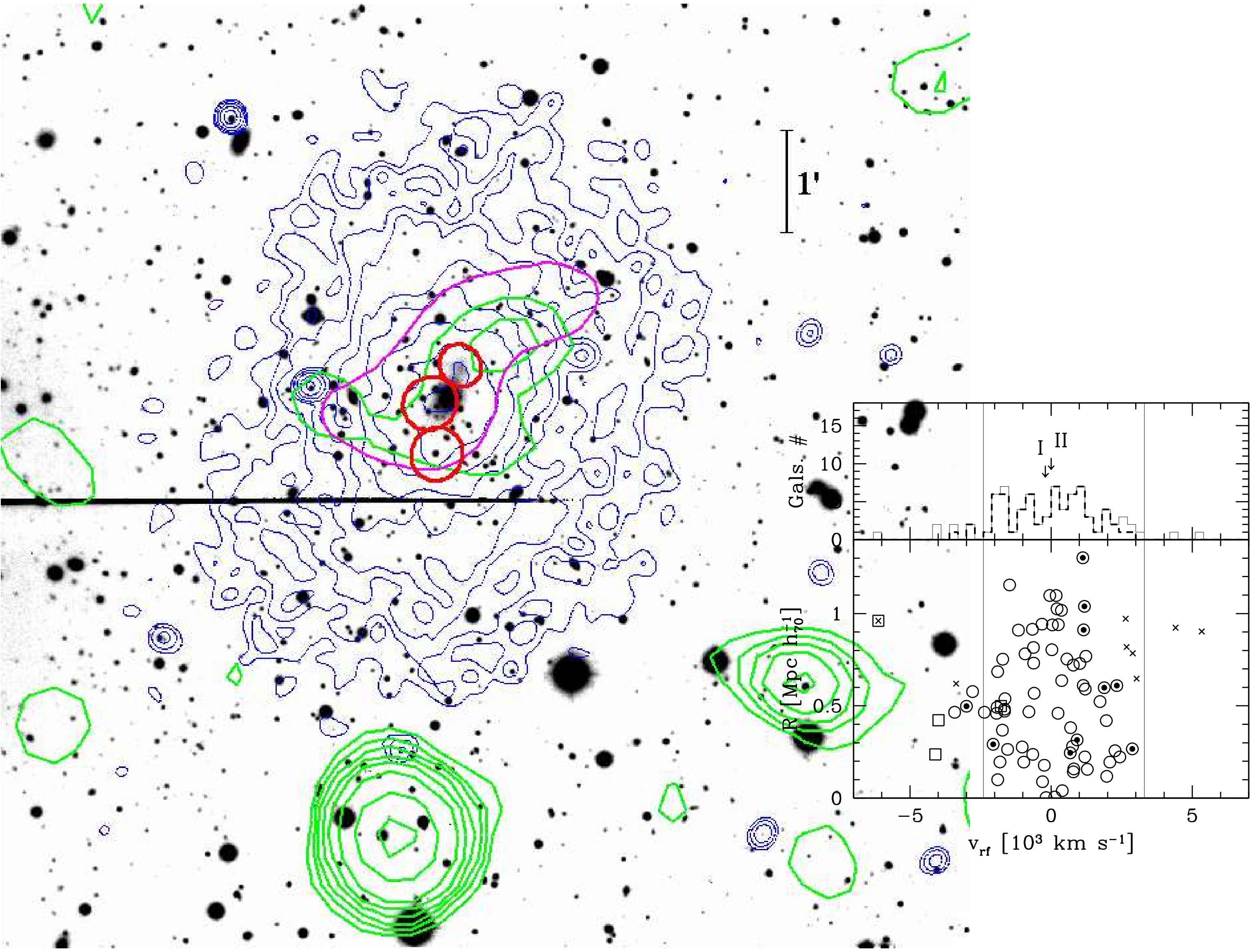
Multiwavelength picture of A520 (North is at the top and East to the left). A smoothed Chandra image (orange and yellow colors) of the central region of A520 (by Markevitch et al. 2005) is superimposed to a r'-band image taken with the WFC camera of the INT. The contour levels of a VLA radio image at 1.4 GHz (by Govoni et al. 2001) are shown, too. Main structures recovered by our analysis are highlighted. Label HVG indicates the center of the high velocity group having a relative LOS velocity of $v_{rf} \sim 2000$ km s^{-1} with respect to the main system (MS). **Blue squares indicate the BCGs for each subcluster.**

Abell 697: an advanced phase of a complex merger?

We compute the line-of-sight (LOS) velocity dispersion of galaxies, $\sigma_{\rm v} = 1334^{+114}_{-95}$ km s^{-1}, in agreement with the high average X-ray temperature $T_{\rm X}$ =(10.2±0.8) keV recovered from Chandra data, as expected in the case of energy-density equipartition between galaxies and gas. Further investigations find that A697 is not fully relaxed, as shown by the non Gaussianity of the velocity distribution, the elongation of the X-ray emission, and the presence of small-size substructures in the central region.

Our results suggest that we are looking to a cluster undergone to a complex cluster merger occurring roughly mainly along the LOS, with a transverse component in the SSE-NNW direction. **The dominant galaxy has a main and a secondary nuclei close in velocity.**

See Girardi et al. (2006, A&A, 455, 45) for other details.



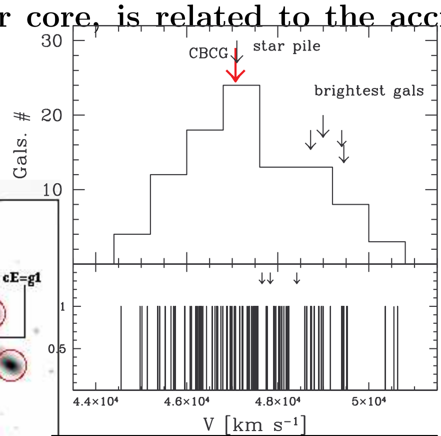
LEFT: R-band image of the cluster A697 with, superimposed, the contour levels of the Chandra image (blue contours) and NVSS radio image (green contours). Red ellipses identify structures detected by Wavdetect. To avoid confusion, only one isodensity contour of the spatial distribution of the (likely) cluster members is shown (magenta). North is at the top and East to the left.

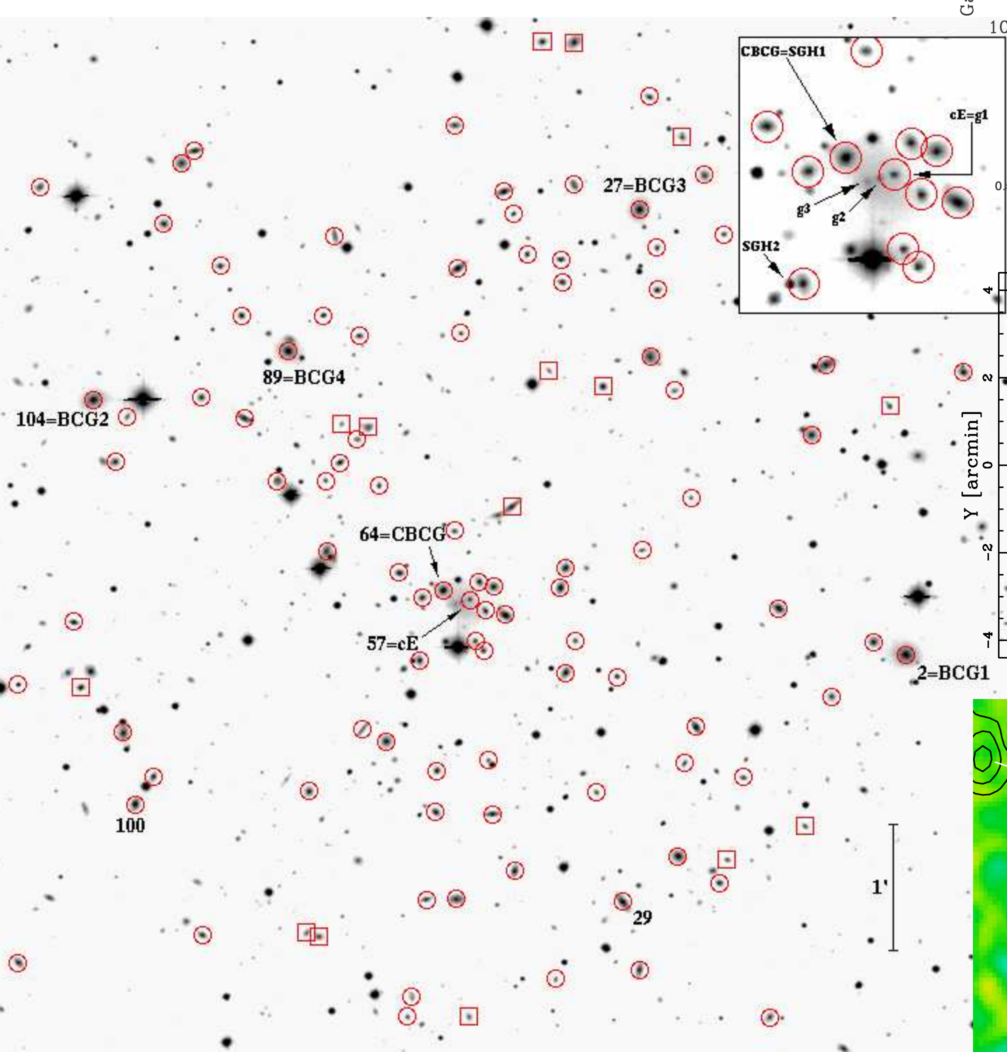
RIGHT: Velocity distribution, where I and II indicate the two nuclei of the BCG, and distribution of cluster galaxies in the velocity-radius plot.

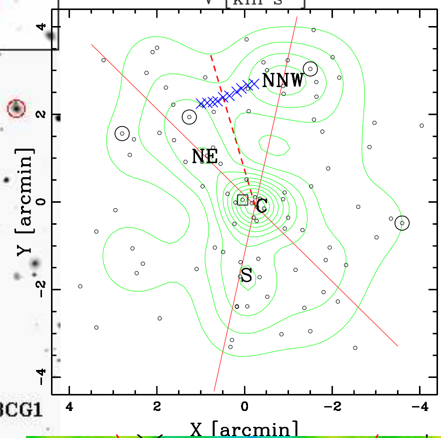
Abell 545: a merging cluster with a forming BCG?

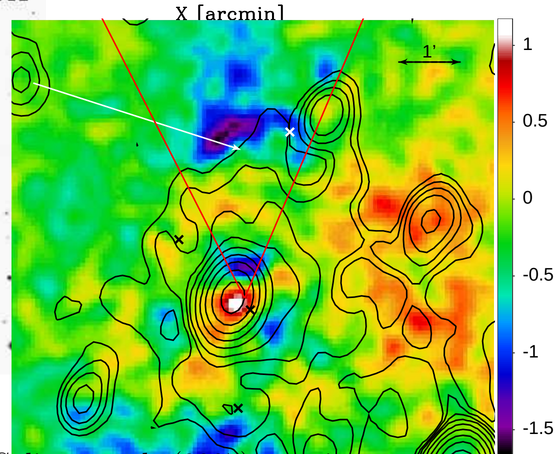
Optical data reveal three main galaxy clumps (one at the center hosting the peak of X-ray emission; one at NNW, and one at NE); and possibly a fourth clump at South. There is not a dominant galaxy and the four brightest galaxies avoid the cluster core. **Two of these brightest galaxies are located in the NNW and NE clumps.** The analysis of the X-ray surface brightness distribution provides us evidence of a disturbed dynamical phase: the strong NNW-SSE elongation, a western excess, and a sharp discontinuity in the northern region which is the likely signature of a shock. Located in the central region there is a bright, red diffuse light and a bright galaxy (CBCG). **We show that the star pile, which has a previously determined redshift (Salinas et al. 2007), has a similar redshift to that of the CBCG and that of the cluster.** The emerging picture of Abell 545 is that of a massive, $M(R < 1.6\ h_{70}^{-1}\mathrm{Mpc}) = (1.1\text{–}1.8) \times 10^{15}\ h_{70}^{-1}\ M_{\odot}$, very complex cluster with merging occurring along two directions. **The star pile, likely due to the process of a brightest galaxy forming in the cluster core, is related to the accretion along the NE direction.**

See Barrena et al. (2011, A&A, 529, A128) for other details.









UPPER: INT r'-band image of the cluster A545.
Circles and squares indicate spectroscopically cluster members and non-members. In the insect figure the corresponding IDs of Salinas et al. (2007) are given, too.

TOP-RIGHT: Velocity distribution.

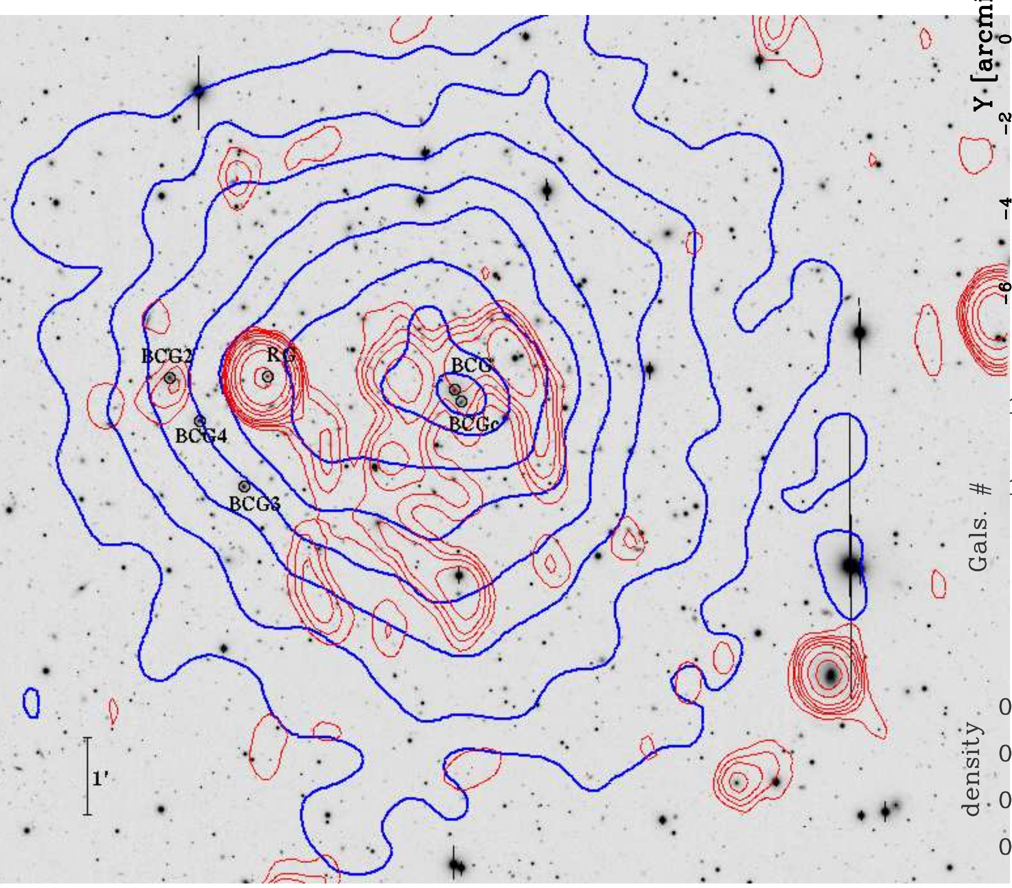
MIDDLE-RIGHT: Spatial distribution and isodensity contours. Circles and square indicate the four brightest galaxies and the CBCG. The two red lines indicate the two likely merging directions. Blue crosses indicate the sharp discontinuity detected in the X-ray surface brightness.

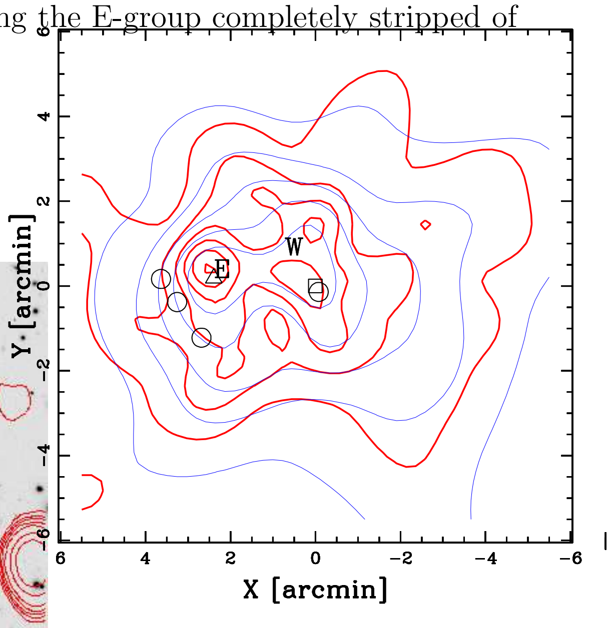
BOTTOM-RIGHT: Residuals of the X-ray surface brightness map (XMM-data) after subtraction of the best fitting elliptical beta model. The black contours show the extended radio emission (Bacchi et al. 2003). The arrow indicates the position of the North surface brightness jump, likely a signature of a shock.

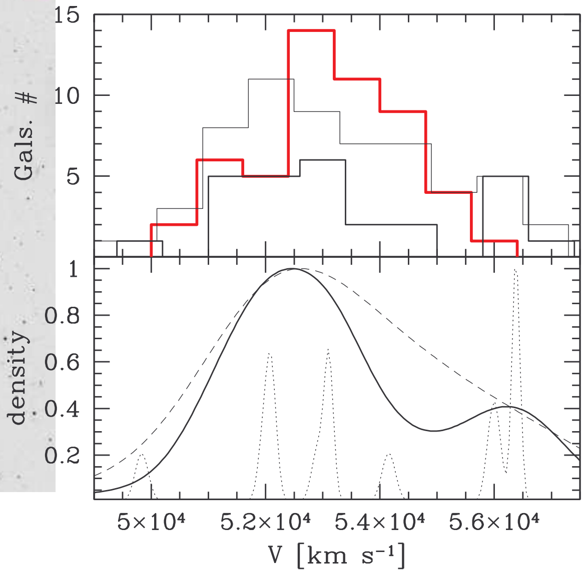
Abell 2254: a merging cluster with a clumpy, diffuse radio emission

We estimate the a high line-of-sight (LOS) velocity dispersion, $\sigma_{\rm V} \sim 1350$ km s^{-1} , and the X-ray temperature $kT \sim$6.4 keV. 2D and 3D analyses show the presence of a eastern high velocity ($\Delta V_{\rm rf,LOS} \sim 3000$ km s^{-1}). The main system is likely substructured, too. The X-ray morphological analysis, based on power ratios, centroid shifts, and concentration parameter, confirms that Abell 2254 is a dynamically disturbed cluster. The X-ray isophotes are elongated toward the eastern direction, in agreement with a merger in the post core-crossing phase. **The E-subcluster does not contain any bright galaxy and is a low mass ($\sigma_{\rm V} \sim$ 200–500 km s^{-1}) group.** This might explain why no secondary X-ray peak is detected, being the E-group completely stripped of its gas content.

See Girardi et al. (2011, A&A, submitted) for other details.







UPPER: Subaru V-band image of the cluster A2254 with (blue) contours of the XMM-image and (red) contours VLA radio image (Govoni et al. 2001).

UPPER-RIGHT: Spatial distribution and isodensity contours of two samples of Subaru photometric cluster members with $i' \leq 20.5$ and with $i' \leq 21.5$ (blue and red contours, respectively).

LOWER-RIGHT: Velocity distributions of the galaxies in the western and eastern samples (red and black lines, respectively). The velocity distribution of a subsample of the eastern sample, i.e. the 27 galaxies within a radius of 1.5′ from the E-peak (E1.5-sample), is also shown (black thick line). In the lower panel, the velocity galaxy density, as provided by the DEDICA adaptive-kernel reconstruction method for the E1.5-sample (solid line).